The anomalous production of multi-leptons and its impact on the measurement of Wh production at the LHC

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Introduction

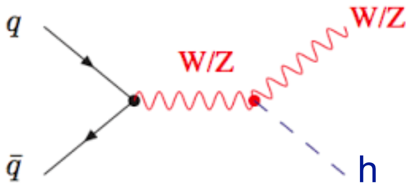
arXiv:1912.00699

ICPP-030

The anomalous production of multi-leptons and its impact on the measurement of Wh production at the LHC

Yesenia Hernandez,[1,*] Alan S. Cornell,[2,†] Mukesh Kumar,[1,‡] Bruce Mellado,[1,3,§] and Xifeng Ruan[1,¶]

Discrepancies in several measurements for the associated production of the SM Higgs (h) with a W boson: Wh



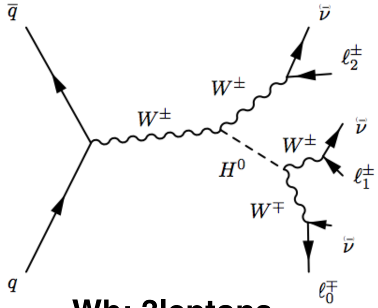
(*) See also talks from B.Mellado and S. von Buddenbrock

Relation with Madala model (*)?

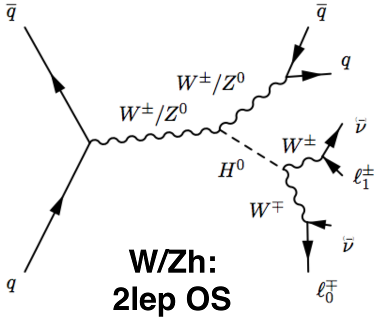
- ATLAS, CMS, Run 1 and 2 results
- Consider results were pT(h) > m(h) is not required for combination
- Investigate each analysis selection
- Compare Vh kinematics with model: H→S[150]h[125] m(H)=250,260,270GeV

Cover h→WW, tautau, yy decay channels

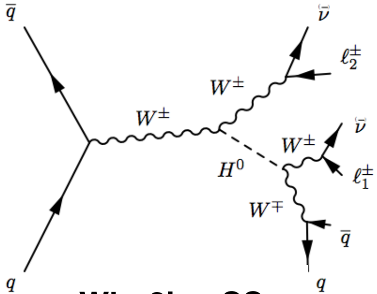
$h \to W W^*$



Wh: 3leptons



W/Zh: 2lep OS



Wh: 2lep SS

arXiv:1506.06641

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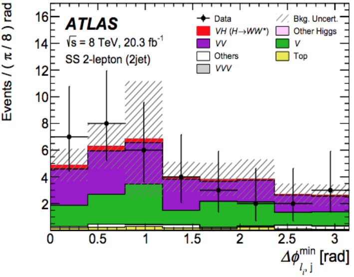
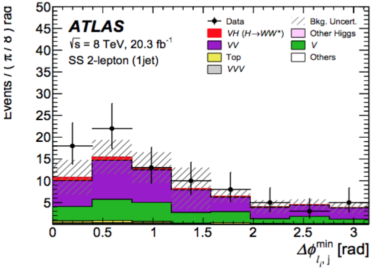
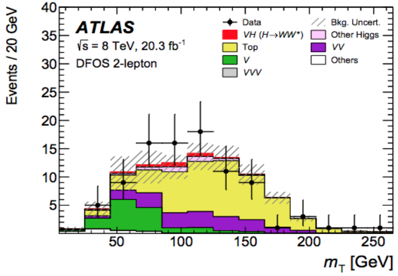
h→ WW: Run 1 ATLAS

Statistically limited analysis but…
Several channels present excesses located at ~ region as the Higgs

Category	Signal significance Z_0: Exp. Z_0	Obs. Z_0	Obs. Z_0	Observed signal strength μ: μ	Tot. err. +	Tot. err. −	Syst. err. +	Syst. err. −	μ
4ℓ	0.41	1.9		**4.9**	4.6	3.1	1.1	0.40	
2SFOS	0.19	0		**−5.9**	6.8	4.1	0.33	0.72	
1SFOS	0.36	2.5		**9.6**	8.1	5.4	2.1	0.64	
3ℓ	0.79	0.66		**0.72**	1.3	1.1	0.40	0.29	
1SFOS and 3SF	0.41	0		**−2.9**	2.7	2.1	1.2	0.92	
0SFOS	0.68	1.2		**1.7**	1.9	1.4	0.51	0.29	
2ℓ	0.59	2.1		**3.7**	1.9	1.5	1.1	1.1	
DFOS	0.54	1.2		**2.2**	2.0	1.9	1.0	1.1	
SS2jet	0.17	1.4		**7.6**	6.0	5.4	3.2	3.2	
SS1jet	0.27	2.3		**8.4**	4.3	3.8	2.3	2.0	
			0 1 2 3						-10 -8 -6 -4 -2 0 2 4 6 8 10 12 14 16

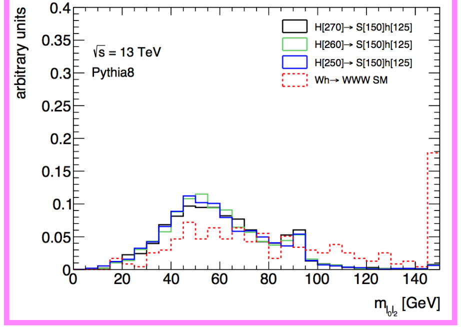






All channels show signal strength > 1
Exception: 3L 1SFOS/3SF uses mll of SS leptons as input BDT variable →

Difference in shape btw Vh and H→Sh
BDT discriminates BSM signal



arXiv:1903.10052

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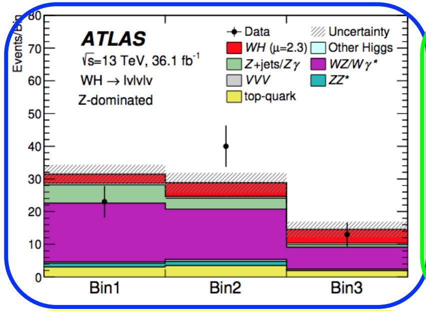
$h \rightarrow WW$: Run 2 ATLAS

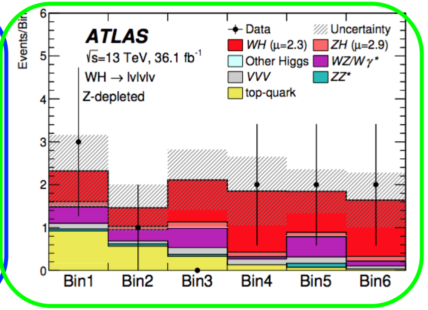
Only 3leptons (BDT) and 4leptons (cut-based) channels are analyzed for the 2015+2016 results

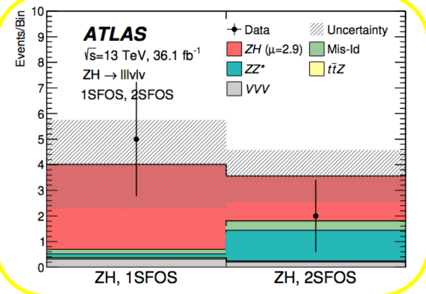
Process	*WH* Z-dominated	*WH* Z-depleted	*ZH* 1-SFOS	*ZH* 2-SFOS
WH	11 ± 6	5.8 ± 2.8	—	
ZH	1.1 ± 0.6	0.61 ± 0.34	3.3 ± 1.7	1.8 ± 0.9
$WZ/W\gamma^*$	40.1 ± 2.8	1.7 ± 0.5	—	
ZZ^*	2.4 ± 1.1	0.27 ± 0.09	0.14 ± 0.14	1.2 ± 0.3
VVV	1.5 ± 0.1	0.71 ± 0.11	0.32 ± 0.05	0.20 ± 0.03
$tV/t\bar{t}V$	0.14 ± 0.03	0.13 ± 0.03	0.04 ± 0.02	0.03 ± 0.01
Other top-quark	8.4 ± 2.6	1.9 ± 0.8	—	
Other Higgs	0.31 ± 0.03	0.06 ± 0.01	<0.01	0.04 ± 0.01
Misid. leptons	9.7 ± 3.4	<0.1	0.19 ± 0.08	0.36 ± 0.12
Total background	62 ± 5	4.7 ± 1.0	0.65 ± 0.17	1.8 ± 0.3
Observed	76	10	5	2

$$\mu_{WH} = 2.3^{+1.1}_{-0.9}(\text{stat.})^{+0.41}_{-0.33}(\text{theo syst.})^{+0.49}_{-0.36}(\text{exp syst.}) = 2.3^{+1.2}_{-1.0},$$

Post-fit results: signal yields weighted by the observed mu!







WH signal strength from the 0SFOS category alone would be larger!

1SFOS/3SF category still uses mll in the BDT
However the signal strength result uses both WH channels so **this will be included in the combination**

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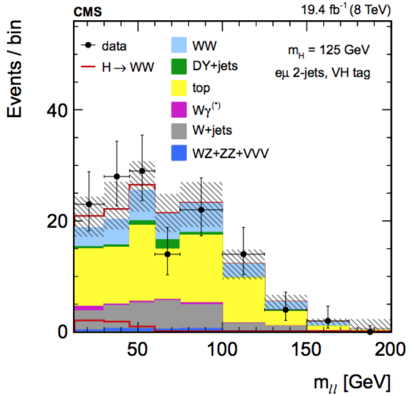
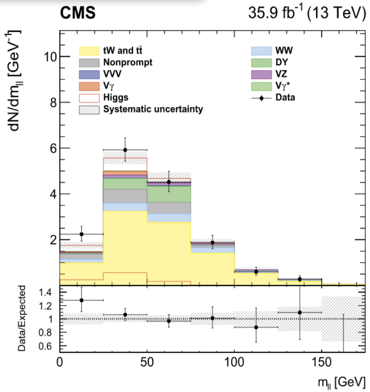
h→ WW: Run 1 and Run 2 CMS

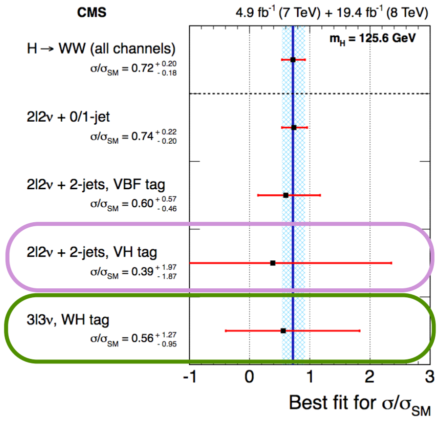
Excess of data at low mll for both Run 1 and Run 2

W/Zh: 2leptons (OS) + 2jets
mjj [65, 105] GeV, |Δη(jj)| < 1.5, mT[60, 125] GeV,
mll < 200 GeV and |ΔR(ll)| < 2.5 → Fit mll in 9 bins

Wh: 3leptons + 3ν
Split in OSSF and SSSF events
min-MET > 40(30) GeV OS(SS), Imll - mZI > 25 GeV,
mll < 100 GeV, IΔR(ll)I < 2 → Fit DeltaR(ll)



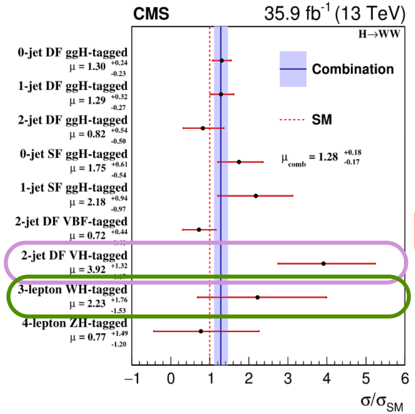


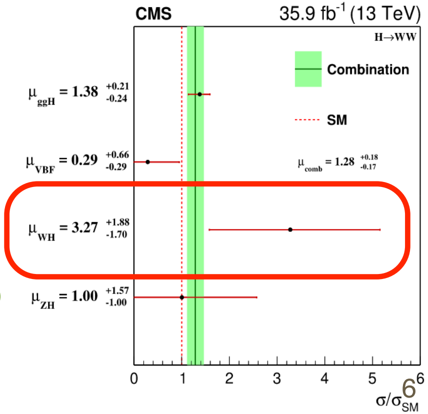


Similar selection in both analyses

Run 1: μ(Wh) < 1 negative fluctuation -left-
Run 2: μ(Wh) > 1 in both channels -right-

Both results will be included in the combination



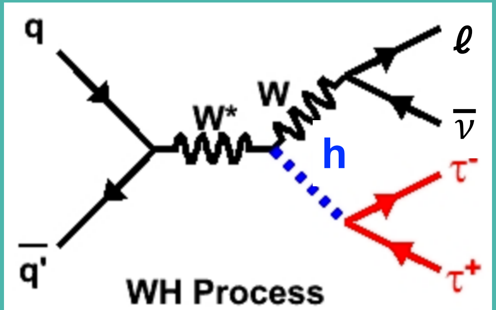


$h \rightarrow \tau\tau$

Strategy: Split in tau decay modes

$h \rightarrow \tau_{had} + \tau_{had}$
$h \rightarrow \tau_{had} + \ell$

W always decaying leptonically: $W \rightarrow \ell\nu$



Two subcategories with 1 or 2 ℓ (e,mu):

1) $\ell + \tau_{had} + \tau_{had}$
2) $\ell + \ell + \tau_{had}$

arXiv:1511.08352 arXiv:1401.5041

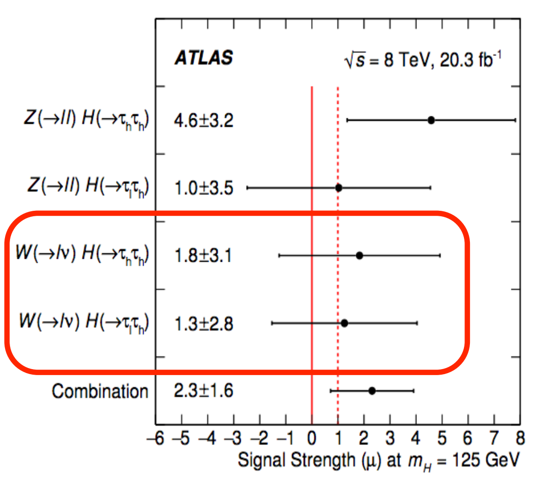
h→ $\tau\tau$: Run 1 ATLAS and CMS

Different analysis selection:

- **ATLAS: Cut&Based**
- **CMS: BDT + LT split**

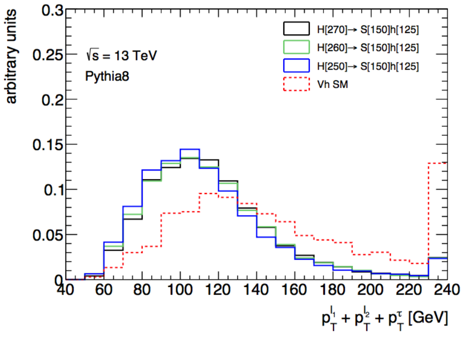
ATLAS:
Bigger excesses (μ > 1) in channels with h → τ_{had}+ τ_{had}

Results from ATLAS included in the combination
CMS results are discarded

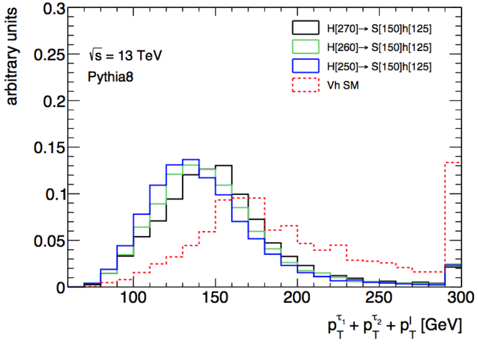


ATLAS > 80 GeV 😀

CMS Split @ 130 GeV ☹️

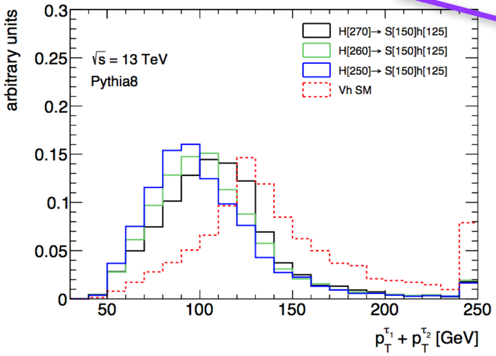


ATLAS > 100 GeV 😀



ATLAS > 100 GeV 😀

CMS used in BDT ☹️



CMS results discarded

- BDT discriminates H→Sh signal
- Split: stat. fit on the SM Vh will concentrate in high region

arXiv:1809.03590

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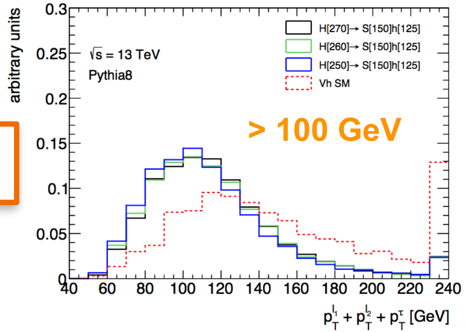
$h \rightarrow \tau\tau$: Run 2 CMS

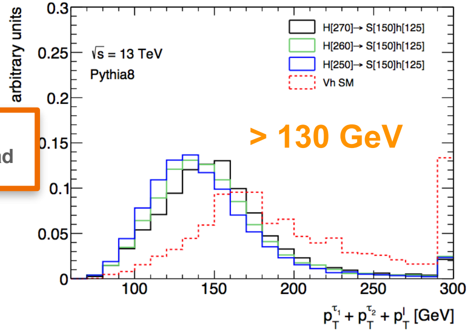
Unfortunately no ATLAS Run 2 results delivered yet

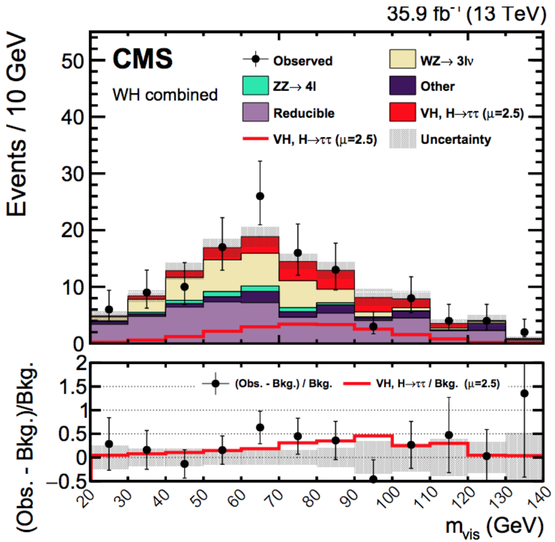
New approach for Run 2 CMS closer to ATLAS: cut&based analysis!

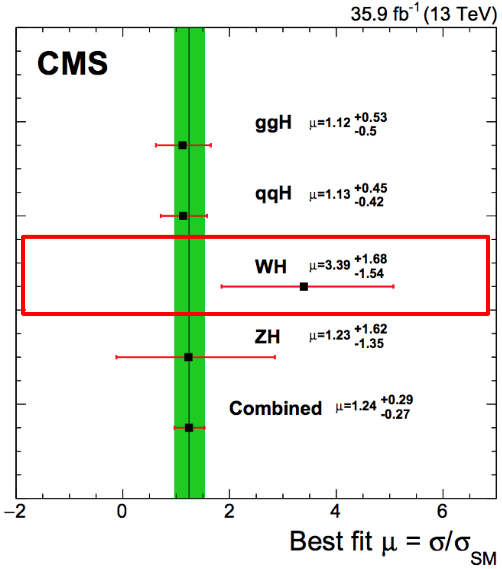
$\ell+\ell+\tau_{had}$



$\ell+\tau_{had}+\tau_{had}$







Fit on visible mass of the taus: $\mu(Wh) = 3.39(+1.68)(-1.54)$

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h→ γγ

VH one-lepton
$(WH \to \ell\nu H)$

↓

$VH\ E_{\mathrm{T}}^{\mathrm{miss}}$
$(ZH \to \nu\nu H;\ WH \to \ell\nu H)$

↓

VH hadronic
$(WH \to jjH;\ ZH \to jjH)$

arXiv:1408.7084, arXiv:1407.0558, arXiv:1802.04146

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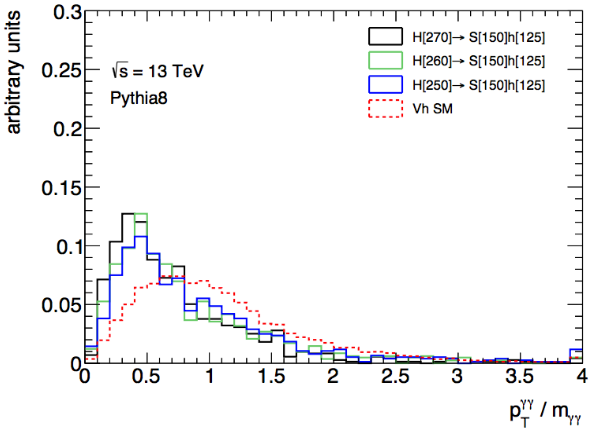
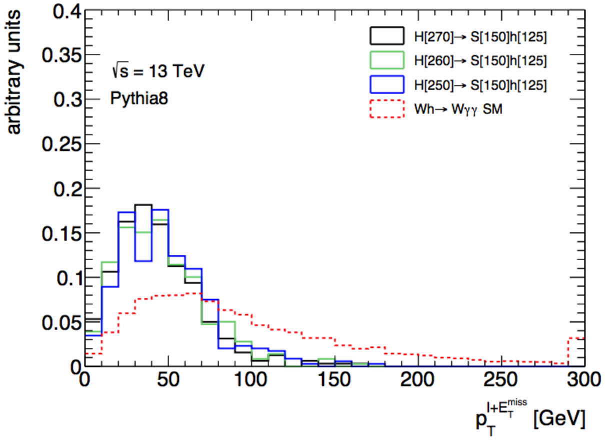
h→ γγ: ATLAS and CMS

Vh Hadronic



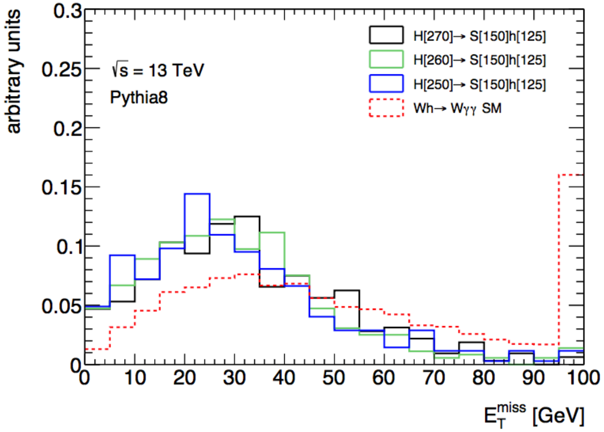
CMS Run 1: pT(γγ) > 13m(γγ)/12
Suppressing most of the H→Sh
Requirement dropped in Run 2

Wh one-lepton



ATLAS Run 2: Split @ 150 GeV
High region (low bkgs) will contribute more in the fit: neglecting H→Sh
Results not included in the combination

Vh ETmiss



All use very high requirements:
ETmiss > 70 - 150 GeV
Category not included in combination

arXiv:1804.02716

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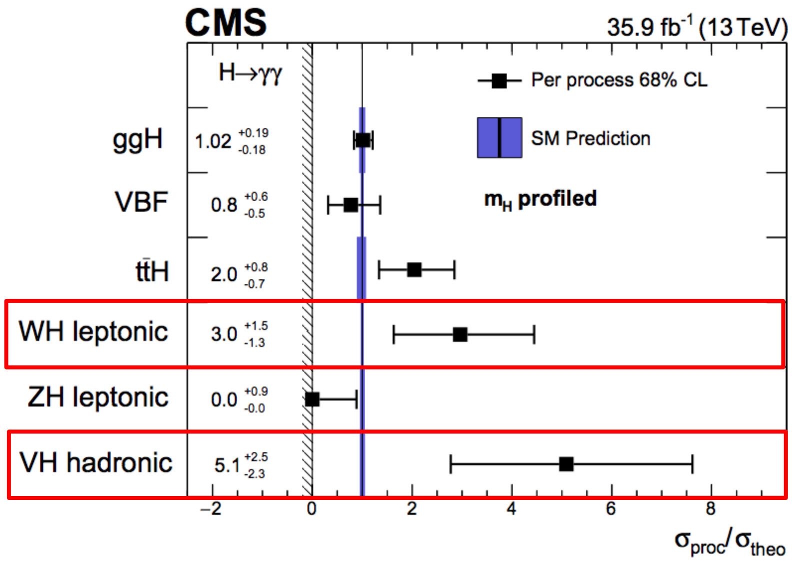
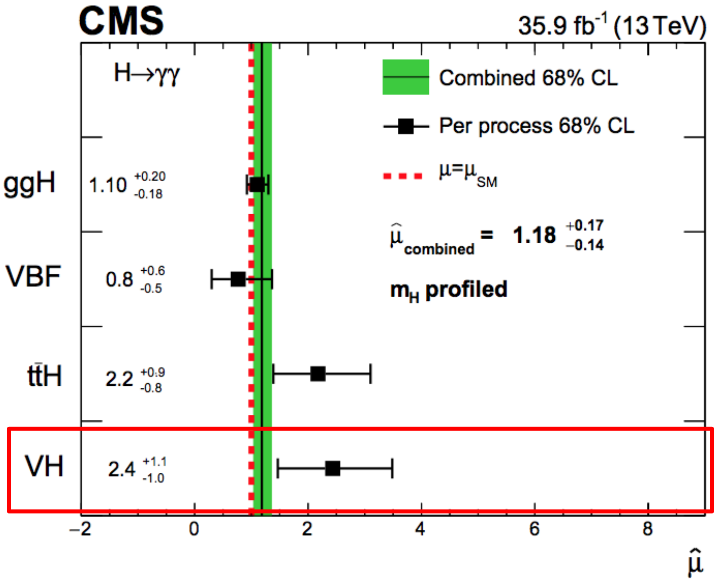
$h \rightarrow \gamma\gamma$: Run 2 CMS



Excesses observed in both:
Wh leptonic and Vh Hadronic

Results will be included in the combination

CMS Run 2 Strategy
Vh Hadronic: No requirement on pt(γγ) / m(γγ)
Vh Leptonic: No use of pT(ℓ+ETmiss)



Combination

arXiv:1912.00699

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Results and Summary

Combined signal strength:
mu_Vh = 2.5 ± 0.43

Deviation from SM: 3.5σ

Larger Wh production than expected by SM

- Excesses observed in very different final states depending on the SM Higgs decay
- Compatible with multi-lepton discrepancies observed at the LHC
- Supports the possible existence of new physics at the LHC: consistent with Madala model

Only partial Run 2 dataset (36.1fb-1) analysed so far…

Much more ATLAS and CMS results to come 😀

Keep posted!

Higgs decay	Ref.	Experiment	$\sqrt{s}$, $\mathcal{L}$ TeV, fb^{-1}	Final state	Category	μ	Used in combination	Comments
WW	[17]	ATLAS	7, 4.5 / 8, 20.3	2ℓ	DFOS 2j	$2.2^{+2.0}_{-1.9}$	✓	
					SS 1j	$8.4^{+4.3}_{-3.8}$	✓	2ℓ combination $\mu = 3.7^{+1.9}_{-1.5}$
					SS 2j	$7.6^{+6.0}_{-5.4}$	✓	
				3ℓ	1SFOS	$-2.9^{+2.7}_{-2.1}$	x	$m_{\ell_0\ell_2}$ used as input BDT discriminating variable
					0SFOS	$1.7^{+1.9}_{-1.4}$	✓	
	[18]	ATLAS	13, 36.1	3ℓ	1SFOS / 0SFOS	$2.3^{+1.2}_{-1.0}$	✓	1SFOS channel uses $m_{\ell_0\ell_2}$ in the BDT but excess driven by 0SFOS
	[19]	CMS	7, 4.9 / 8, 19.4	2ℓ	DFOS 2j	$0.39^{+1.97}_{-1.87}$	✓	Discrepancy at low $m_{\ell\ell}$
				3ℓ	0+1SFOS	$0.56^{+1.27}_{-0.95}$	✓	
	[20]	CMS	13, 35.9	2ℓ	DFOS 2j	$3.92^{+1.32}_{-1.17}$	✓	Discrepancy at low $m_{\ell\ell}$
				3ℓ	0+1SFOS	$2.23^{+1.76}_{-1.53}$	✓	
$\tau\tau$	[21]	ATLAS	8, 20.3	1ℓ	$\ell + \tau_h\tau_h$	1.8 ± 3.1	✓	
				2ℓ	$e^\pm\mu^\pm + \tau_h$	1.3 ± 2.8	✓	
	[22]	CMS	7, 4.9 / 8, 19.7	1ℓ	$\ell + \tau_h\tau_h$	-0.33 ± 1.02	x	BDT based on $p_T^{\tau_1} + p_T^{\tau_2}$
				2ℓ	$e^\pm\mu^\pm + \tau_h$		x	Split $p_T^{\ell_1} + p_T^{\ell_2} + p_T^{\tau}$ at 130 GeV
	[23]	CMS	13, 35.9	1ℓ	$\ell + \tau_h\tau_h$	$3.39^{+1.68}_{-1.54}$	✓	
				2ℓ	$e^\pm\mu^\pm + \tau_h$			
$\gamma\gamma$	[24]	ATLAS	7, 5.4 / 8, 20.3	$\ell\nu$	one-lepton	1.0 ± 1.6	x	
				$\ell\nu, \nu\nu$	E_T^{miss}			$E_T^{miss} > 70 - 100$ GeV
				jj	Hadronic			$p_{Tt}^{\gamma\gamma} > 70$ GeV
	[25]	CMS	7, 5.1 / 8, 19.7	$\ell\nu$	one-lepton	$-0.16^{+1.16}_{-0.79}$	x	Split E_T^{miss} at 45 GeV
				$\ell\nu, \nu\nu$	E_T^{miss}			$E_T^{miss} > 70$ GeV
				jj	Hadronic			$p_T^{\gamma\gamma} > 13m_{\gamma\gamma}/12$
	[26]	ATLAS	13, 36.1	$\ell\nu$	one-lepton	$0.7^{+0.9}_{-0.8}$	x	$p_T^{\ell+E_T^{miss}} > 150$ GeV; $p_T^{\ell+E_T^{miss}} < 150$ GeV
				$\ell\nu, \nu\nu$	E_T^{miss}			$150 < E_T^{miss} < 250$ GeV; $80 < E_T^{miss} < 150$ GeV
				jj	Hadronic			BDT used based on m_{jj} and $p_{Tt}^{\gamma\gamma}$
	[27]	CMS	13, 35.6	$\ell\nu$	one-lepton	$2.4^{+1.1}_{-1.0}$	✓	Split E_T^{miss} at 45 GeV ($\mu = 3.0^{+1.5}_{-1.3}$)
				$\ell\nu, \nu\nu$	E_T^{miss}		x	$E_T^{miss} > 85$ GeV
				jj	Hadronic		✓	$p_T^{\gamma\gamma}/m_{\gamma\gamma}$ not used ($\mu = 5.1^{+2.5}_{-2.3}$)

Thank you!

Backup Slides

Summary

ATLAS

Run 1

o H→ WW https://arxiv.org/pdf/1506.06641.pdf

mu_VH = 3.0 +1.3(+1.0) -1.1(-0.7) stat(syst);
mu_WH= 2.1 +1.5(+1.2) -1.3(-0.8)
mu_ZH = 5.1 +3.8(+1.9) -3.0(-0.9)

o H→ tautau https://arxiv.org/pdf/1511.08352.pdf

mu_VH = 2.3 +/- 1.6

o H → yy https://arxiv.org/pdf/1408.7084.pdf

mu_WH = 1.0 +/- 1.6, mu_ZH = 0.1 +3.7 -0.1

Run 2

o H→ WW https://arxiv.org/pdf/1903.10052.pdf

mu_VH = 2.5 +0.9 -0.8;
mu_WH = 2.3 +1.2 -1.0, mu_ZH= 2.9 +1.9 -1.3

o H→ tautau https://arxiv.org/pdf/1811.08856.pdf

Inclusive mu = 1.09 +0.18(+0.26) -0.17(-0.22) stat(sys)

o H→ yy https://arxiv.org/pdf/1802.04146.pdf

mu_VH = 0.7 +0.9 -0.8

CMS

Run 1

o H→ WW https://arxiv.org/pdf/1312.1129.pdf

mu_VH_2l = 0.39 +1.97 -1.87,
mu_WH = 0.56 +1.27 -0.95, mu_ZH = 6.41 +7.43 -6.38

o H→ tautau https://arxiv.org/pdf/1401.5041.pdf

mu_VH_tag = -0.33 +/- 1.02

o H→ yy https://arxiv.org/pdf/1407.0558.pdf

mu_VH = -0.16 +/- 0.97

Run 2

o H→ WW https://www.sciencedirect.com/science/article/pii/S0370269319301169

mu_WH = 3.27 +1.88 -1.70, mu_ZH = 1.00 +1.57 -1.00

o H→ tautau https://arxiv.org/pdf/1809.03590.pdf

mu_VH = 2.5 +1.4 -1.0
mu_WH = 3.39 +1.62 -1.35, mu_ZH = 1.23 +1.62 -1.35

o H→ yy https://arxiv.org/pdf/1804.02716.pdf

mu_VH = 2.4 +1.1 -1.0

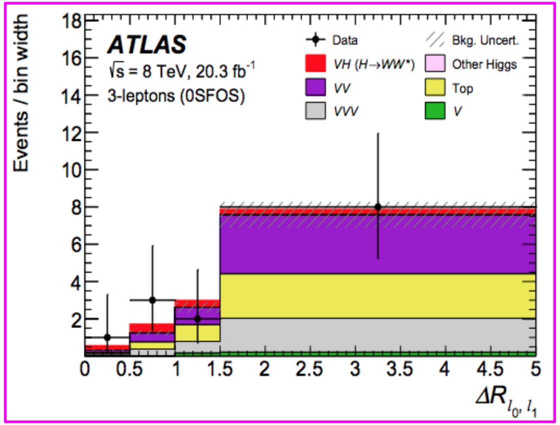
arXiv:1506.06641

H→ WW: Run 1 ATLAS

Channel	4ℓ		3ℓ			2ℓ		
Category	2SFOS	1SFOS	3SF	1SFOS	0SFOS	DFOS	SS2jet	SS1jet
Trigger	single-lepton triggers		single-lepton triggers			single-lepton & dilepton triggers		
Num. of leptons	4	4	3	3	3	2	2	2
$p_{\mathrm{T,leptons}}$ [GeV]	$> 25, 20, 15$	$> 25, 20, 15$	> 15	> 15	> 15	$> 22, 15$	$> 22, 15$	$> 22, 15$
Total lepton charge	0	0	±1	±1	±1	0	±2	±2
Num. of SFOS pairs	2	1	2	1	0	0	0	0
Num. of jets	≤ 1	≤ 1	≤ 1	≤ 1	≤ 1	≥ 2	2	1
$p_{\mathrm{T,jets}}$ [GeV]	> 25 (30)	> 25 (30)	> 25 (30)	> 25 (30)	> 25 (30)	> 25 (30)	> 25 (30)	> 25 (30)
Num. of b-tagged jets	0	0	0	0	0	0	0	0
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 20	> 20	> 30	> 30	—	> 20	> 50	> 45
$p_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 15	> 15	> 20	> 20	—	—	—	—
$\lvert m_{\ell\ell} - m_Z \rvert$ [GeV]	< 10 ($m_{\ell_2\ell_3}$)	< 10 ($m_{\ell_2\ell_3}$)	> 25	> 25	—	—	> 15	> 15
Min. $m_{\ell\ell}$ [GeV]	> 10 ($m_{\ell_0\ell_1}$)	> 10 ($m_{\ell_0\ell_1}$)	> 12	> 12	> 6	> 10	> 12 ($ee, \mu\mu$)	> 12 ($ee, \mu\mu$)
							> 10 ($e\mu$)	> 10 ($e\mu$)
Max. $m_{\ell\ell}$ [GeV]	< 65 ($m_{\ell_0\ell_1}$)	< 65 ($m_{\ell_0\ell_1}$)	< 200	< 200	< 200	< 50	—	—
$m_{4\ell}$ [GeV]	> 140	—	—	—	—	—	—	—
$p_{\mathrm{T},4\ell}$ [GeV]	> 30	—	—	—	—	—	—	—
$m_{\tau\tau}$ [GeV]	—	—	—	—	—	$< (m_Z - 25)$	—	—
$\Delta R_{\ell_0\ell_1}$	—	—	< 2.0	< 2.0	—	—	—	—
$\Delta\phi_{\ell_0\ell_1}$ [rad]	< 2.5 ($\Delta\phi_{\ell_0\ell_1}^{\mathrm{boost}}$)	< 2.5 ($\Delta\phi_{\ell_0\ell_1}^{\mathrm{boost}}$)	—	—	—	< 1.8	—	—
m_{T} [GeV]	—	—	—	—	—	< 125	—	> 105 ($m_{\mathrm{T}}^{\mathrm{lead}}$)
Min. $m_{\ell_i j(j)}$ [GeV]	—	—	—	—	—	—	< 115	< 70
Min. $\phi_{\ell_i j}$ [rad]	—	—	—	—	—	—	< 1.5	< 1.5
Δy_{jj}	—	—	—	—	—	< 1.2	—	—
$\lvert m_{jj} - 85 \rvert$ [GeV]	—	—	—	—	—	< 15	—	—

arXiv:1506.06641

H→ WW: Run 1 ATLAS

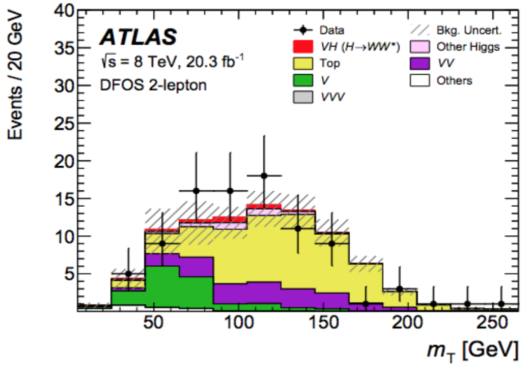


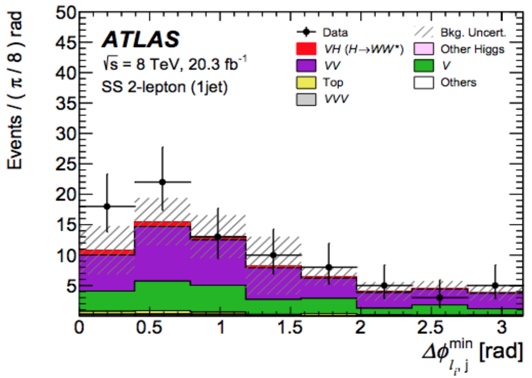
Process	4ℓ		3ℓ			2ℓ		
Category	2SFOS	1SFOS	3SF	1SFOS	0SFOS	DFOS	SS2jet	SS1jet
Higgs boson								
$VH\ (H \to WW^*)$	0.203±0.030	0.228±0.034	0.73±0.10	1.61±0.18	1.43±0.16	2.15±0.30	1.04±0.18	2.04±0.30
$VH\ (H \to \tau\tau)$	0.0084±0.0032	0.012±0.004	0.057±0.011	0.152±0.023	0.248±0.035	—	0.036±0.008	0.27±0.04
ggF	—	—	0.076±0.015	0.085±0.018	—	2.4±0.5	—	—
VBF	—	—	—	—	—	0.180±0.025	—	—
ttH	—	—	—	—	—	—	—	—
Background								
V	—	—	0.22±0.16	1.9±0.6	0.37±0.15	14±4	8±4	15±5
VV	1.17±0.20	0.31±0.06	19±3	28±4	4.7±0.6	10.1±1.6	11.2±2.1	26±4
VVV	0.12±0.04	0.10±0.04	0.8±0.3	2.2±0.7	2.93±0.29	—	—	0.47±0.05
Top	0.014±0.011	—	0.91±0.26	2.4±0.6	3.7±0.9	24±4	0.75±0.19	1.3±0.5
Others	—	—	—	—	—	2.3±0.9	0.71±0.30	0.60±0.24
Total	1.30±0.23	0.41±0.09	22±4	34±6	11.7±1.8	50±5	21±5	44±6
Observed events	0	3	22	38	14	63	25	62

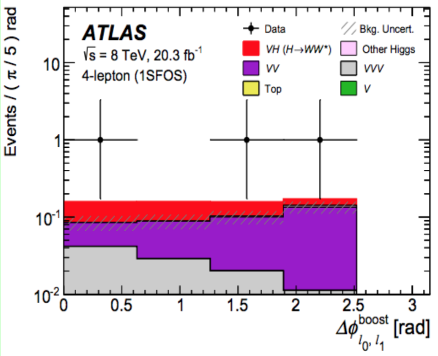
https://arxiv.org/pdf/1506.06641.pdf

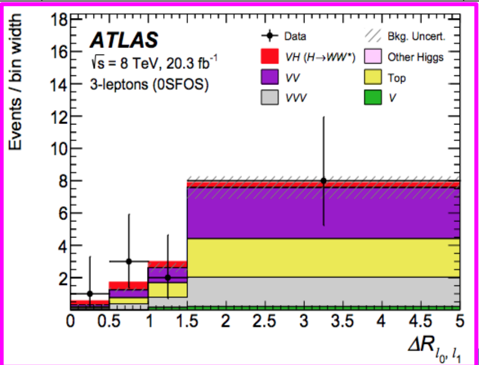
H→ WW: Run 1 ATLAS

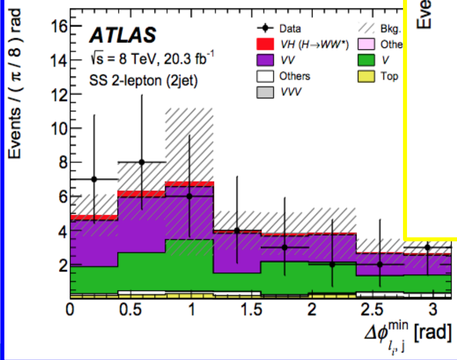
Process	4ℓ		3ℓ			2ℓ		
Category	2SFOS	1SFOS	3SF	1SFOS	0SFOS	DFOS	SS2jet	SS1jet
Higgs boson								
VH ($H \to WW^*$)	0.203±0.030	0.228±0.034	0.73±0.10	1.61±0.18	1.43±0.16	2.15±0.30	1.04±0.18	2.04±0.30
VH ($H \to \tau\tau$)	0.0084±0.0032	0.012±0.004	0.057±0.011	0.152±0.023	0.248±0.035	—	0.036±0.008	0.27±0.04
ggF	—	—	0.076±0.015	0.085±0.018	—	2.4±0.5	—	—
VBF	—	—	—	—	—	0.180±0.025	—	—
ttH	—	—	—	—	—	—	—	—
Background								
V	—	—	0.22±0.16	1.9±0.6	0.37±0.15	14±4	8±4	15±5
VV	1.17±0.20	0.31±0.06	19±3	28±4	4.7±0.6	10.1±1.6	11.2±2.1	26±4
VVV	0.12±0.04	0.10±0.04	0.8±0.3	2.2±0.7	2.93±0.29	—	—	0.47±0.05
Top	0.014±0.011	—	0.91±0.26	2.4±0.6	3.7±0.9	24±4	0.75±0.19	1.3±0.5
Others	—	—	—	—	—	2.3±0.9	0.71±0.30	0.60±0.24
Total	1.30±0.23	$\boxed{0.41±0.09}$	22±4	34±6	$\boxed{11.7±1.8}$	$\boxed{50±5}$	$\boxed{21±5}$	$\boxed{44±6}$
Observed events	0	$\boxed{3}$	22	38	$\boxed{14}$	$\boxed{63}$	$\boxed{25}$	$\boxed{62}$











https://www.sciencedirect.com/science/article/pii/S0370269319301169

H→ WW: Run 2 CMS

Category	Subcategory	Requirements
Preselection	–	$m_{\ell\ell} > 12$ GeV, $p_{T1} > 25$ GeV, $p_{T2} > 13$ (10) GeV for e (μ) $p_T^{miss} > 20$ GeV, $p_T^{\ell\ell} > 30$ GeV no additional leptons with $p_T > 10$ GeV electron and muon with opposite charges
2-jet VH-tagged	eμ	at least two jets with $p_T > 30$ GeV two leading jets with $\lvert\eta\rvert < 2.5$ $60 < m_T < 125$ GeV and $\Delta R_{\ell\ell} < 2$ no b-tagged jets with $p_T > 20$ GeV $65 < m_{jj} < 105$ GeV and $\lvert\Delta\eta_{jj}\rvert < 3.5$

Category	Subcategory	Requirements
Preselection	–	$p_{T1} > 25$ GeV, $p_{T2} > 20$ GeV, $p_{T3} > 15$ GeV no additional leptons with $p_T > 10$ GeV min–$m_{\ell^+\ell^-} > 12$ GeV, total lepton charge sum ± 1
3-lepton WH-tagged	OSSF	no jets with $p_T > 30$ GeV no b-tagged jets with $p_T > 20$ GeV $p_T^{miss} > 50$ GeV, min–$m_{\ell^+\ell^-} < 100$ GeV Z boson veto: $\lvert m_{\ell\ell} - m_Z\rvert > 25$ GeV $\Delta\phi(\ell\ell\ell, \vec{p}_T^{miss}) > 2.2$
	SSSF	no jets with $p_T > 30$ GeV no b-tagged jets with $p_T > 20$ GeV $\Delta\phi(\ell\ell\ell, \vec{p}_T^{miss}) > 2.5$

Category	Subcategory	Requirements
Preselection	–	four tight and isolated leptons, with zero total charge $p_T > 25$ GeV for the leading lepton $p_T > 15$ GeV for the second leading lepton $p_T > 10$ GeV for the remaining two leptons no additional leptons with $p_T > 10$ GeV Z dilepton mass > 4 GeV X dilepton mass > 4 GeV no b-tagged jets with $p_T > 20$ GeV
4-lepton ZH-tagged	XSF	$\lvert m_{\ell\ell} - m_Z\rvert < 15$ GeV $10 < m_X < 50$ GeV $35 < p_T^{miss} < 100$ GeV four-lepton invariant mass > 140 GeV
	XDF	$\lvert m_{\ell\ell} - m_Z\rvert < 15$ GeV $10 < m_X < 70$ GeV $p_T^{miss} > 20$ GeV

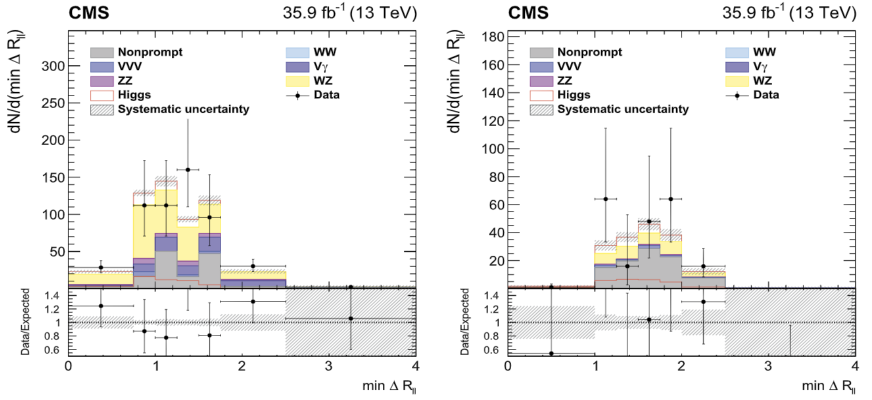


Fig. 6. Postfit $\Delta R_{\ell\ell}$ distribution for events in the three-lepton WH-tagged category, split into the OSSF (left) and SSSF (right) subcategories.

https://arxiv.org/pdf/1506.06641.pdf

H→ WW: Run 1 ATLAS

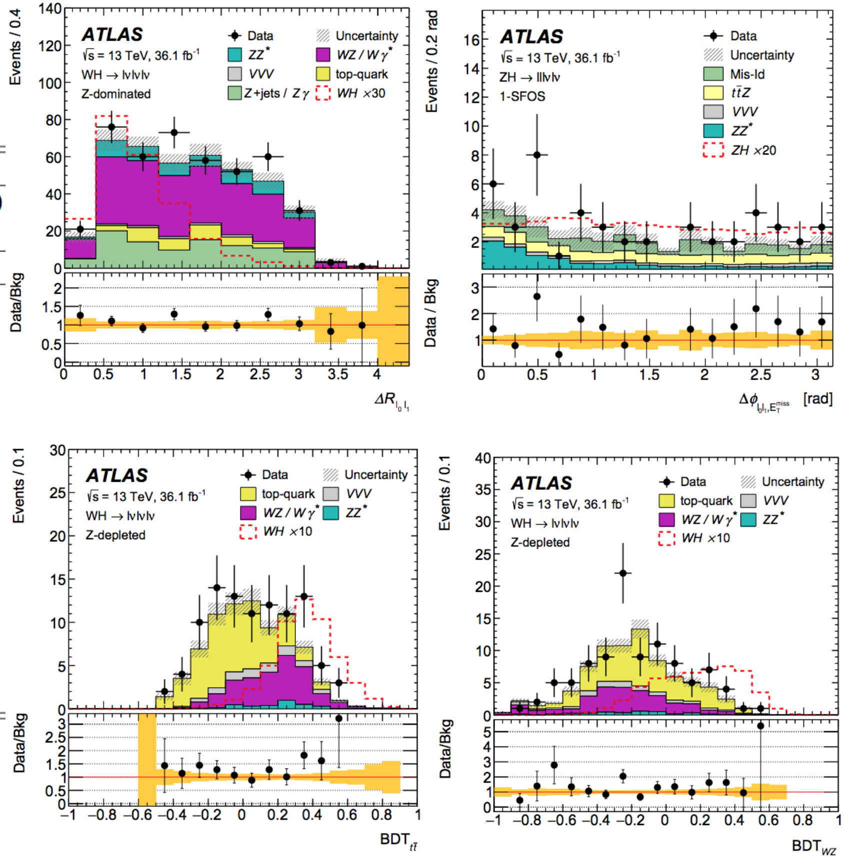
3 leptons: 1SFOS and 3SF → BDT INPUT VARIABLES

BDT input discriminating variables which provide the best separation between signal and background are the p_{T} of each lepton, the magnitude of their vector sum, the invariant masses of the two opposite-sign lepton pairs ($m_{\ell_0\ell_1}$, $m_{\ell_0\ell_2}$), $\Delta R_{\ell_0\ell_1}$, $E_{\mathrm{T}}^{\mathrm{miss}}$, and $p_{\mathrm{T}}^{\mathrm{miss}}$. In the fit, the shape of the distribution of the "BDT Score", divided into six bins, is used to extract the number of observed events in the 3ℓ-3SF and 3ℓ-1SFOS SRs, while the shape of the distribution of $\Delta R_{\ell_0\ell_1}$, divided into four bins, is used to extract the number of observed events in the 3ℓ-0SFOS SR. In the other channels only the event yield in each signal and control region is used without shape information.

https://arxiv.org/pdf/1903.10052.pdf

H→ WW: Run 2 ATLAS

	WH		*ZH*	
Preselection	3 isolated leptons ($p_{\mathrm{T}} > 15$ GeV) total lepton charge ±1		4 isolated leptons ($p_{\mathrm{T}} > 10$ GeV) total lepton charge 0	
Category	Z-dominated	Z-depleted	2-SFOS	1-SFOS
Number of SFOS	2 or 1	0	2	1
Number of jets	≤ 1	—	≤ 1	≤ 2
Number of b-jets	0	0	0	0
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 30	—	> 45	—
$p_{\mathrm{T}}^{4\ell}$ [GeV]	—	—	> 45	—
$m_{\ell\ell}$ [GeV]	> 12 (min. SFOS)	—	> 10	> 10
$\lvert m_{\ell\ell} - m_Z \rvert$ [GeV]	> 25 (SFOS)	—	< 10 ($m_{\ell_2\ell_3}$)	< 10 ($m_{\ell_2\ell_3}$)
$m_{\ell_0\ell_1}$ [GeV]	—	—	< 55	< 60
$\Delta\phi_{\ell_0\ell_1}^{\mathrm{boost}}$	—	—	< 2.3	< 1.9
$m_{\tau\tau}$ [GeV]	—	—	—	< 50
$\Delta\phi_{\ell_0\ell_1, E_{\mathrm{T}}^{\mathrm{miss}}}$ [rad]	—	—	—	> 0.4
$m_{4\ell}$ [GeV]	—	—	> 140	—
BDT	$\mathrm{BDT}_{\mathrm{Zdom}} > 0.3$	$\mathrm{BDT}_{t\bar{t}} > 0.2$ & $\mathrm{BDT}_{WZ} > 0.15$	—	—



Only 3leptons (BDT) and 4leptons (cut-based) channels were analyzed for the 2015+2016 results

https://arxiv.org/pdf/1903.10052.pdf

H→ WW: Run 2 ATLAS

3 leptons: BDT input variables

Lepton nomenclature
(l0l1 assumed from H decay -see slide 4-)

l0: lepton with different charge

l1: lepton closest to lepton l0

l2: remaining lepton

Table 7: Input variables of the three BDT discriminants used in the 3ℓ channel.

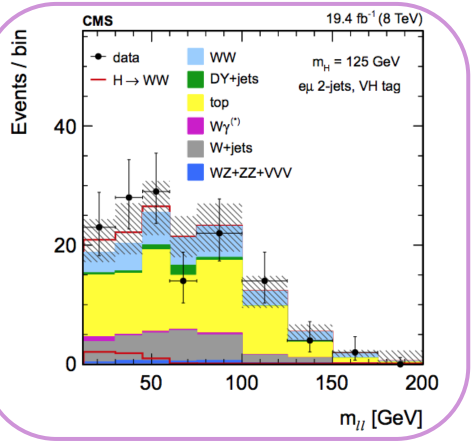
Input variable	Z-dominated	Z-depleted BDT_{WZ}	Z-depleted $\mathrm{BDT}_{t\bar{t}}$
$\lvert\Sigma\mathbf{p}_{\mathrm{T}}^{\ell_i}\rvert$	x		
$m_{\ell_0\ell_1}$	x	x	x
$m_{\ell\ell\ell}$	x		
$\Delta R_{\ell_0\ell_1}$	x		x
$E_{\mathrm{T}}^{\mathrm{miss}}$	x	x	
$\Delta\eta_{\ell_1\ell_2}$	x	x	x
m_{T}^{W}	x		
$p_{\mathrm{T}}^{\ell_0}$		x	
$p_{\mathrm{T}}^{\ell_1}$		x	
$p_{\mathrm{T}}^{\ell_2}$		x	
$m_{\ell_0\ell 1}^{\mathrm{T}}$		x	
m_{ee}		x	
$\lvert d_{0,\mathrm{sig,min}}\rvert$		x	
$\lvert d_{0,\mathrm{sig,mid}}\rvert$		x	
F_α		x	
$\mathrm{BDT}_{\mathrm{HFL}}$ output for ℓ_{HFL}			x
$p_{\mathrm{T}}^{\ell_{\mathrm{HFL}}}$			x
$m_{\ell_{\mathrm{HFL}}\ell_{\mathrm{cloc}}}$			x
N_{jet}			x
$p_{\mathrm{T}}^{j_{\mathrm{lead}}}$			x
$m_{\ell_1\ell_2}$			x

arXiv:1312.1129

H→ WW: Run 1 CMS

W/ZH: 2leptons + 2jets

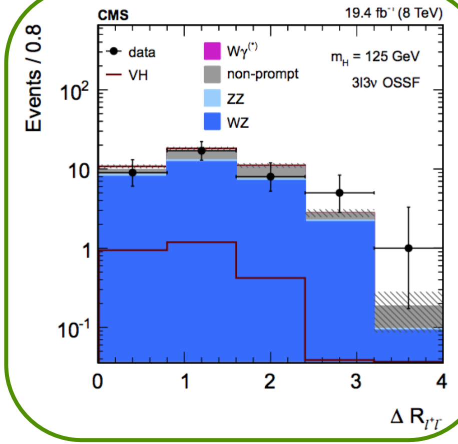
mjj [65, 105] GeV, IDeltaEtajjl < 1.5,
mT [60, 125] GeV, mll < 200 GeV and DeltaR < 2.5
→ Fit mll in 9 bins

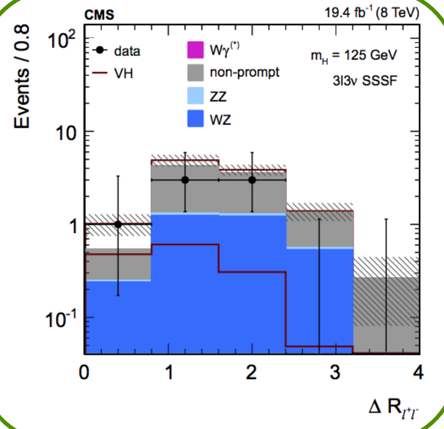


Accumulation of data at low mll but limited statistics with Run 1

WH: 3leptons + 3v

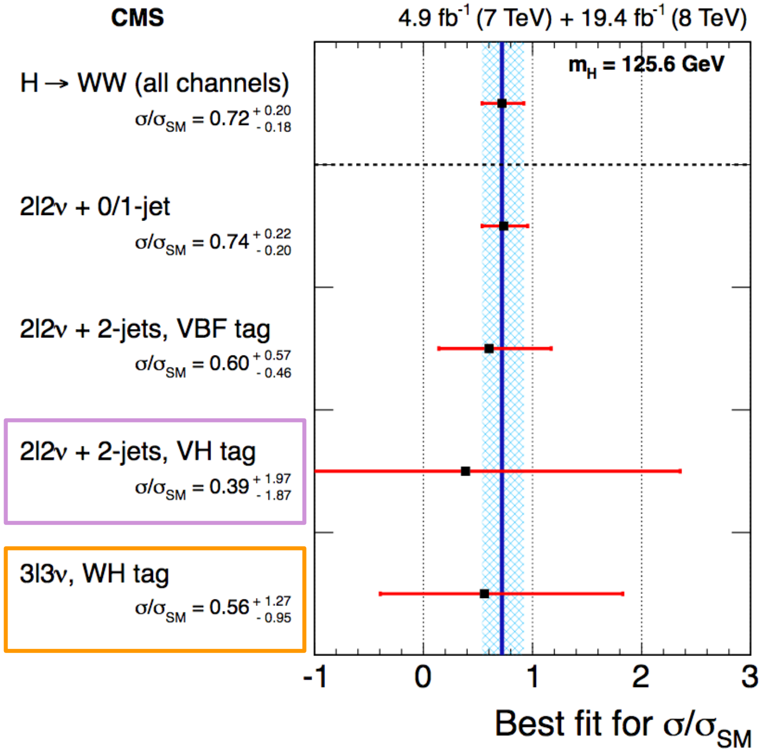
Split in OSSF and SSSF events
min-MET > 40(30) GeV OS(SS), Imll - mZl > 25 GeV, mll < 100 GeV, DeltaRll < 2
→ Fit DeltaR(ll)





arXiv:1312.1129

H→ WW: Run 1 CMS



m_H [GeV]	ggH	VBF+VH	Data	All bkg.	WW	WZ + ZZ + Z/$\gamma^* \to \ell\ell$	$t\bar{t}$ + tW	W + jets
8 TeV eμ final state, 2-jets category, VH tag								
125 (shape)	2.86 ± 0.92	2.30 ± 0.18	136	129 ± 15	28.3 ± 6.2	8.2 ± 1.3	67 ± 13	23.9 ± 4.8

Selection stage	WH $H \to \tau\tau$	WH $H \to WW$	Data	All bkg.	WZ	Non-prompt
8 TeV SSSF final state, WH → $3\ell3\nu$ category						
3 lepton requirement	0.72 ± 0.08	1.64 ± 0.21	71	83.7 ± 3.0	7.88 ± 0.30	66.8 ± 2.9
Min-MET > 30 GeV	0.41 ± 0.06	1.21 ± 0.18	43	60.2 ± 2.5	5.16 ± 0.24	48.4 ± 2.5
Z removal	0.41 ± 0.06	1.21 ± 0.18	43	60.2 ± 2.5	5.16 ± 0.24	48.4 ± 2.5
Top-quark veto	0.29 ± 0.05	1.02 ± 0.17	7	10.41 ± 0.97	2.84 ± 0.18	6.60 ± 0.95
$\Delta R_{\ell^+\ell^-}$ & $m_{\ell\ell}$	0.23 ± 0.05	1.00 ± 0.20	6	6.9 ± 2.0	1.71 ± 0.16	4.6 ± 2.0
8 TeV OSSF final state, WH → $3\ell3\nu$ category						
3 lepton requirement	1.95 ± 0.12	6.08 ± 0.41	4340	4224 ± 21	2042.7 ± 4.8	1369.0 ± 13
Min-MET > 40 GeV	0.91 ± 0.09	3.47 ± 0.30	1137	1140.9 ± 6.0	900.0 ± 3.2	149.9 ± 4.9
Z removal	0.56 ± 0.07	2.69 ± 0.27	153	155.3 ± 3.4	59.1 ± 0.8	79.9 ± 3.3
Top-quark veto	0.35 ± 0.05	2.14 ± 0.23	45	47.7 ± 1.3	34.9 ± 0.6	9.6 ± 1.2
$\Delta R_{\ell^+\ell^-}$ & $m_{\ell\ell}$	0.30 ± 0.06	2.10 ± 0.34	33	33.2 ± 3.4	24.0 ± 1.4	7.2 ± 3.1

https://arxiv.org/pdf/1511.08352.pdf

H→ tautau: Run 1 ATLAS

Channel	Selections
$W \to \mu\nu/e\nu,\ \ H \to \tau_{\rm lep}\tau_{\rm had}$	Exactly one isolated electron and one isolated muon Exactly one $\tau_{\rm had}$ passing medium BDT ID $p_{\rm T}(\tau_{\rm had}) > 25$ GeV Same-charge e and μ, oppositely charged $\tau_{\rm had}$ Events containing b-tagged jets with $p_{\rm T} > 30$ GeV are vetoed $\lvert p_{\rm T}(\tau_{\rm had})\rvert + \lvert p_{\rm T}(\mu)\rvert + \lvert p_{\rm T}(e)\rvert > 80$ GeV $\Delta R(\tau_{\rm had}, \tau_{\rm lep}) < 3.2$
$W \to \mu\nu/e\nu,\ \ H \to \tau_{\rm had}\tau_{\rm had}$	Exactly one isolated electron or one isolated muon Exactly two $\tau_{\rm had}$ passing medium BDT ID of opposite charge $p_{\rm T}(\tau_{\rm had}) > 20$ GeV $\lvert p_{\rm T}(\tau^1_{\rm had})\rvert + \lvert p_{\rm T}(\tau^2_{\rm had})\rvert > 100$ GeV $m_{\rm T}(\ell, E_{\rm T}^{\rm miss}) > 20$ GeV $0.8 < \Delta R(\tau^1_{\rm had}, \tau^2_{\rm had}) < 2.8$ Events containing b-tagged jets with $p_{\rm T} > 30$ GeV are vetoed
$Z \to \mu\mu/ee,\ \ H \to \tau_{\rm lep}\tau_{\rm had}$	Exactly three electrons or muons, One opposite-charge and same-flavor lepton pair with invariant mass $80 < m_{\ell\ell} < 100$ GeV Exactly one $\tau_{\rm had}$ passing medium BDT ID, with opposite charge to the lepton assigned to the Higgs boson $p_{\rm T}(\tau_{\rm had}) > 20$ GeV $\lvert p_{\rm T}(\tau_{\rm had})\rvert + \lvert p_{\rm T}(\tau_{\rm lep})\rvert > 60$ GeV
$Z \to \mu\mu/ee,\ \ H \to \tau_{\rm had}\tau_{\rm had}$	Exactly two electrons or two muons of opposite charge Exactly two $\tau_{\rm had}$ passing medium BDT ID of opposite charge $p_{\rm T}(\tau_{\rm had}) > 20$ GeV $60 < m_{\ell\ell} < 120$ GeV $\lvert p_{\rm T}(\tau^1_{\rm had})\rvert + \lvert p_{\rm T}(\tau^2_{\rm had})\rvert > 88$ GeV

Strategy: Split in tau decay modes

H→ tau_had + tau_had
H→ tau_had + tau_lep

while V always decaying leptonically: W→ lv / Z→ ll

Two subcategories in each channel
WH: 1 or 2 leptons (e,mu)
ZH: 2 or 3 leptons

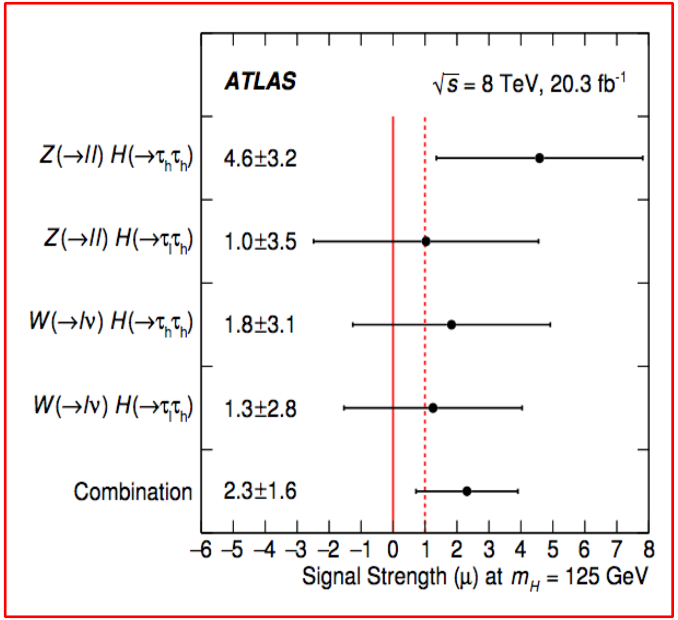
Table 5: The yields for the observed and expected background and signal for a 125 GeV Higgs boson in the signal region for each individual channel. The "other" column consists primarily of background from $t\bar{t}$ events. The uncertainties quoted are statistical only.

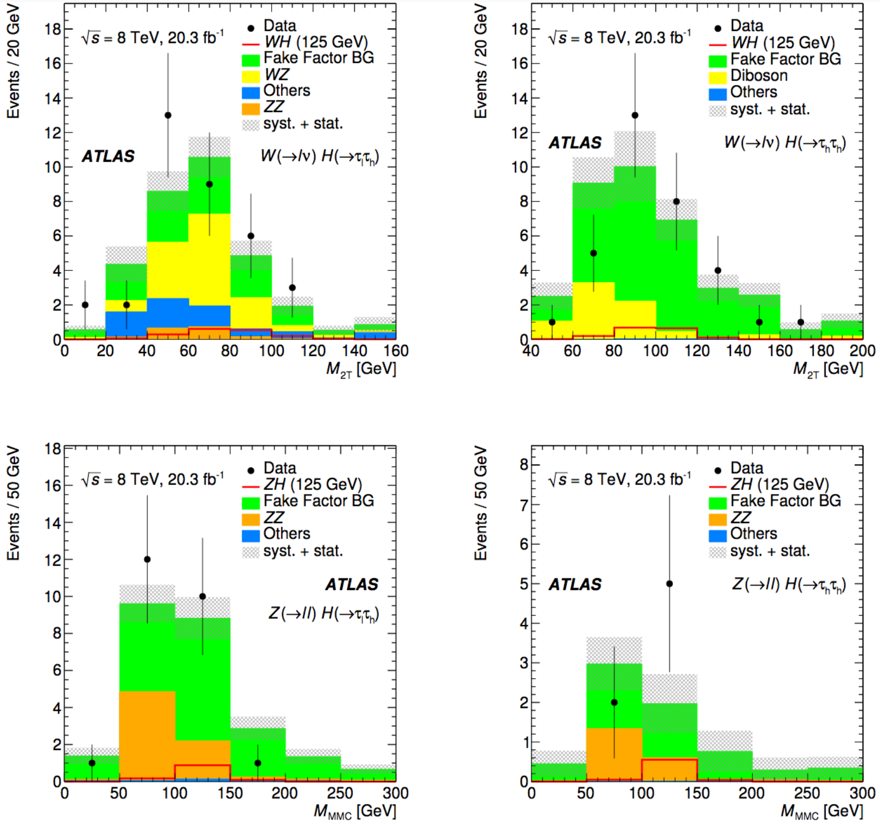
Channel	Obs.	Signal	Σ Background	Fake Factor	Diboson	Other
$W \to \mu\nu/e\nu,\ \ H \to \tau_{\rm lep}\tau_{\rm had}$	35	1.95 ± 0.05	32.4 ± 1.9	13.1 ± 1.3	13.54 ± 0.35	5.7 ± 1.4
$W \to \mu\nu/e\nu,\ \ H \to \tau_{\rm had}\tau_{\rm had}$	33	1.84 ± 0.04	35.5 ± 2.7	28.1 ± 2.4	7.4 ± 1.2	-
$Z \to \mu\mu/ee,\ \ H \to \tau_{\rm lep}\tau_{\rm had}$	24	1.14 ± 0.03	24.6 ± 1.5	17.1 ± 1.5	7.28 ± 0.16	0.20 ± 0.01
$Z \to \mu\mu/ee,\ \ H \to \tau_{\rm had}\tau_{\rm had}$	7	0.64 ± 0.02	6.8 ± 1.2	4.7 ± 1.2	2.09 ± 0.09	0.012 ± 0.003

Fit to the MMC (M2T) shape in ZH (WH)

https://arxiv.org/pdf/1511.08352.pdf

H→ tautau: Run 1 ATLAS





Bigger excesses in channels with H→ tau_had + tau_had

mu >= 1 for all cases

Unfortunately, no ATLAS Run-2 analysis (yet) → Only ggf+VBF in Run-2 https://arxiv.org/pdf/1811.08856.pdf

H→ tautau: Run 1 CMS

- **WH: l + L tau_had**
- **ZH: ll + LL'**

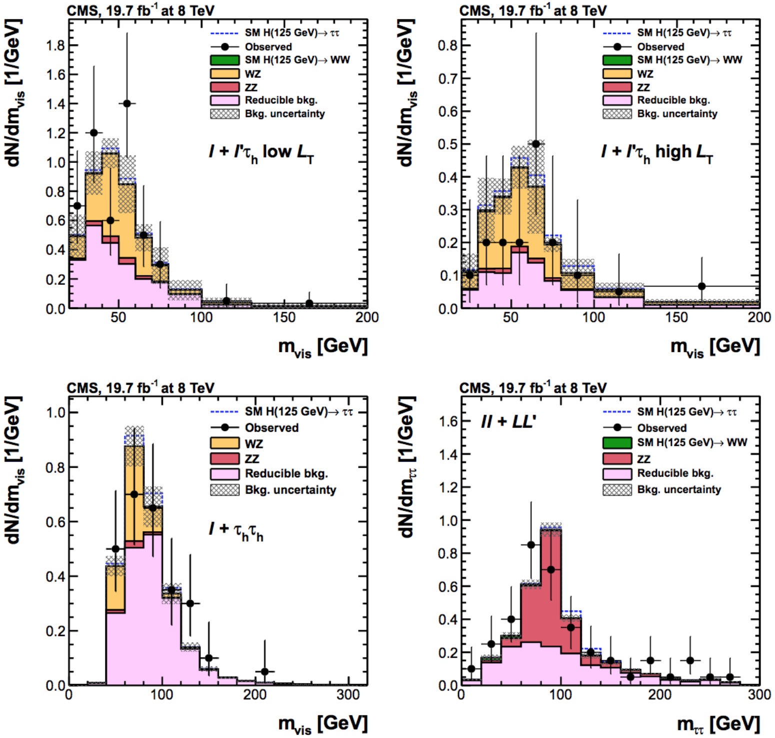
where l = e,mu and L = l or tau_had

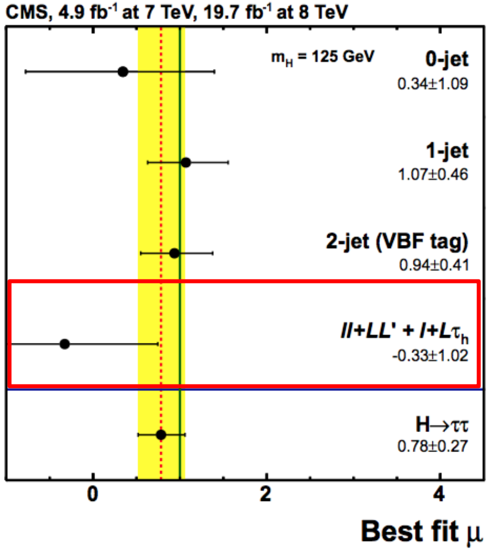
→ l + l' tau_had channel

- ll' are SS to reduce Z and tt
- Split in LT <(>) 130 GeV

→ ll + LL'

- ll are OSSF
- Split in LT(LL') = pT(L) + pT(L') > 25 - 70 GeV depending on the lepton flavour





mu_VH = -0.33 +/- 1.02

https://arxiv.org/pdf/1401.5041.pdf

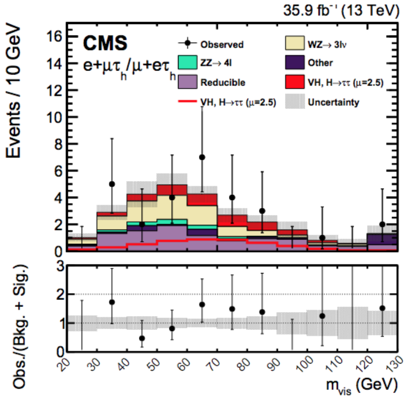
H→ tautau: Run 1 CMS

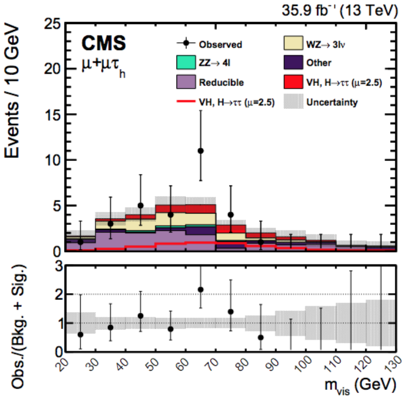
In the $\ell + \tau_h\tau_h$ channels, the background from QCD multijet, W + jets, and Z + jets production is suppressed using a BDT discriminant based on the E_T^{miss} and on kinematic variables related to the $\tau_h\tau_h$ system. With $\tau_{h,1}$ and $\tau_{h,2}$ denoting the τ_h with highest and second-highest p_T, respectively, these variables are $p_T^{\tau_{h,1}}$, $p_T^{\tau_{h,2}}$, $\Delta R(\tau_{h,1}, \tau_{h,2})$, and $p_T^{\tau_{h,1},\tau_{h,2}} / (p_T^{\tau_{h,1}} + p_T^{\tau_{h,2}})$. For the chosen threshold on the BDT score, the signal efficiency is ~60% whereas the efficiency for the reducible background components is ~13%.

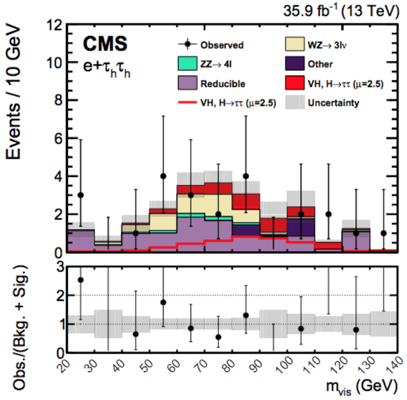
In the $\ell + \ell'\tau_h$ channels, the large background from Z and $t\bar{t}$ production is strongly reduced by requiring the ℓ and ℓ' leptons to have the same charge. For the 7 TeV dataset, the requirement $L_T \equiv p_T^{\ell} + p_T^{\ell'} + p_T^{\tau_h} > 80\,\text{GeV}$ is imposed to further suppress the reducible background components. For the 8 TeV dataset, the L_T variable is instead used to divide the data into two event categories, one with high L_T ($\geq$130 GeV) and one with low L_T (<130 GeV). The Z + jets

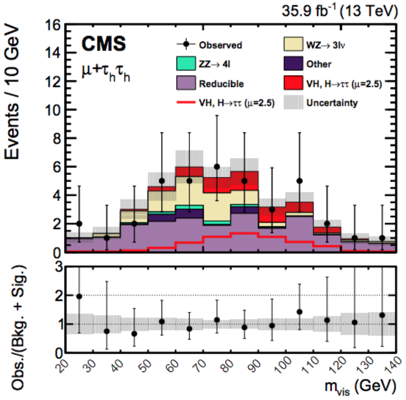
https://arxiv.org/pdf/1809.03590.pdf

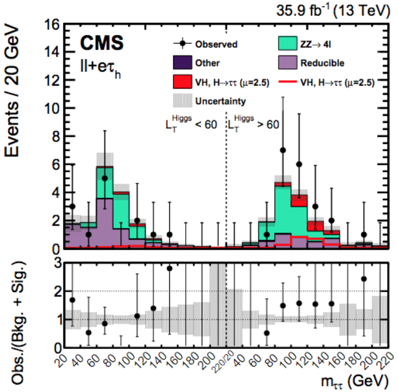
H→ tautau: Run 2 CMS

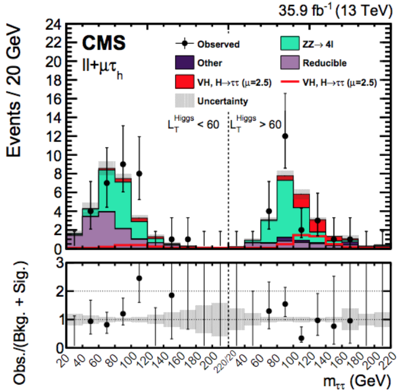


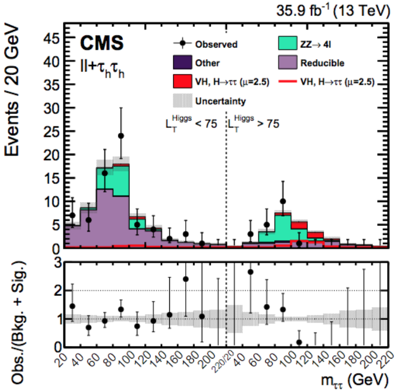


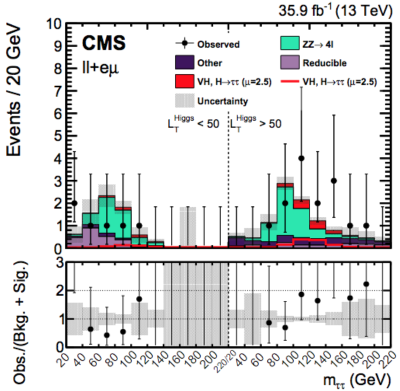






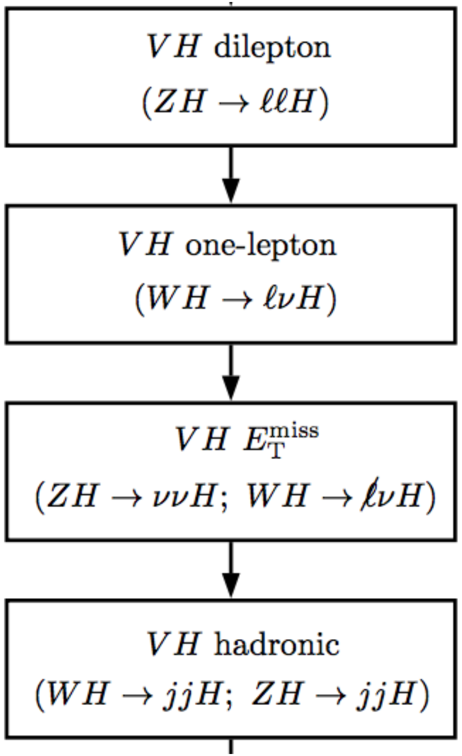


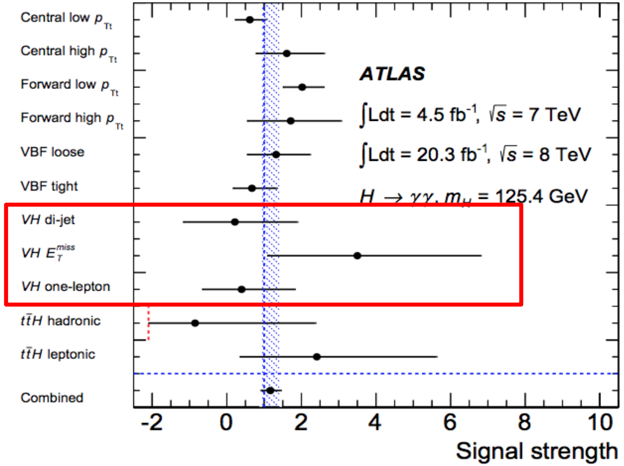


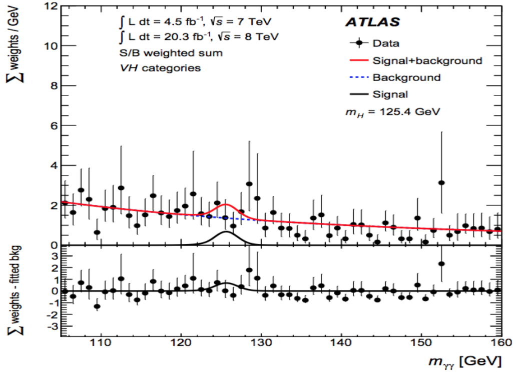


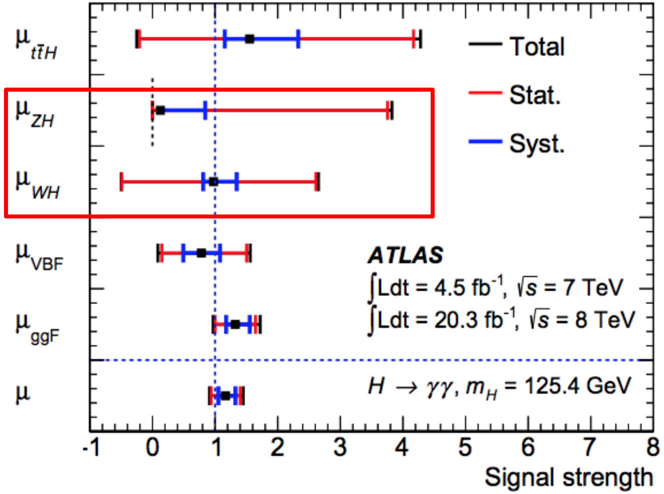
https://arxiv.org/pdf/1408.7084.pdf

H→ γγ: Run 1 ATLAS









$$\mu_{WH} = 1.0 \pm 1.5\ (\text{stat.})\ ^{+0.3}_{-0.1}\ (\text{syst.})\ ^{+0.2}_{-0.1}\ (\text{theory})$$

$$\mu_{ZH} = 0.1\ ^{+3.6}_{-0.1}\ (\text{stat.})\ ^{+0.7}_{-0.0}\ (\text{syst.})\ ^{+0.1}_{-0.0}\ (\text{theory})$$

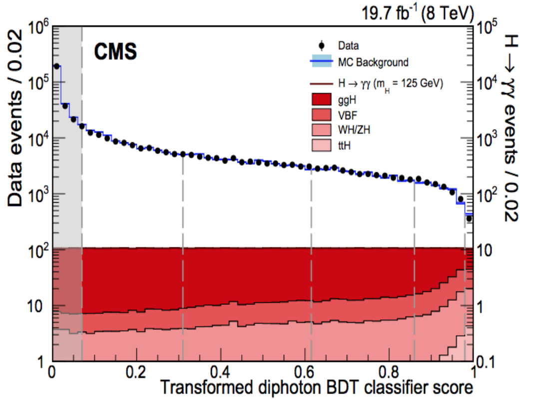
https://arxiv.org/pdf/1407.0558.pdf

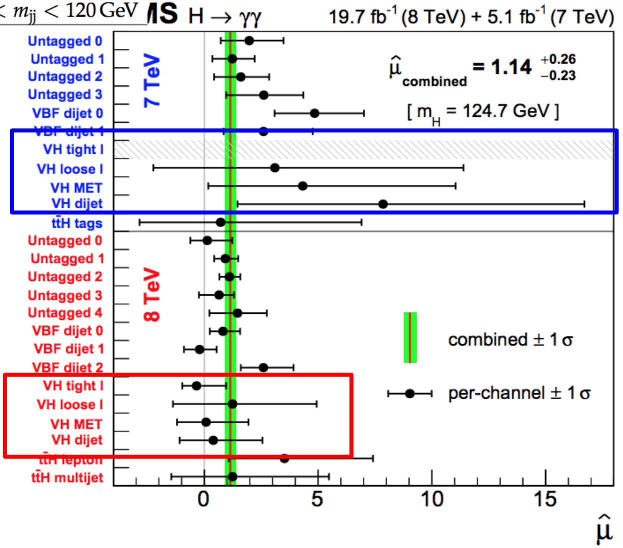
H→ γγ: Run 1 CMS

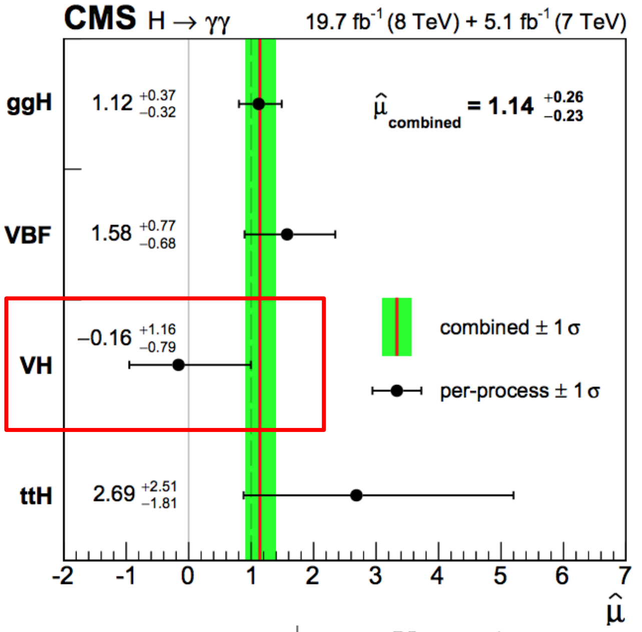
Label	No. of classes 7 TeV	No. of classes 8 TeV	Main requirements
VH tight ℓ tag	1	1	$p_T^{\gamma 1} > 3m_{\gamma\gamma}/8$ [e or μ, $p_T > 20\,\text{GeV}$, and $E_T^{\text{miss}} > 45\,\text{GeV}$] or [2e or 2$\mu$, $p_T^{\ell} > 10\,\text{GeV}$; $70 < m_{\ell\ell} < 110\,\text{GeV}$]
VH loose ℓ tag	1	1	$p_T^{\gamma 1} > 3m_{\gamma\gamma}/8$ e or μ, $p_T > 20\,\text{GeV}$
VH E_T^{miss} tag	1	1	$p_T^{\gamma 1} > 3m_{\gamma\gamma}/8$ $E_T^{\text{miss}} > 70\,\text{GeV}$
VH dijet tag	1	1	$p_T^{\gamma 1} > m_{\gamma\gamma}/2$ jet pair, $p_T^{j} > 40\,\text{GeV}$ and $60 < m_{jj} < 120\,\text{GeV}$

Four VH classes

Make use of diphoton BDT classifier for entry into the different classes





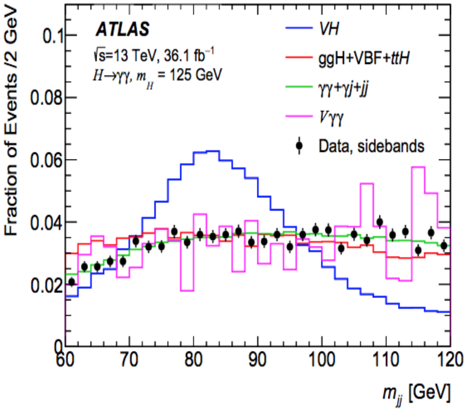


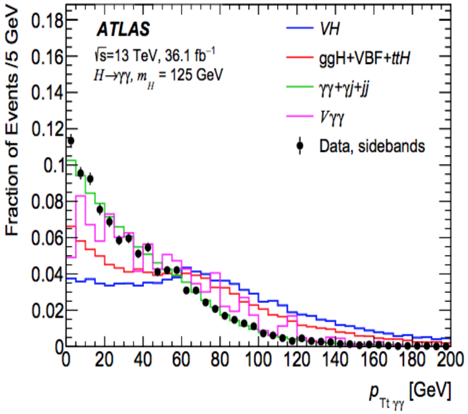
Process	$\hat{\mu}$	Uncertainty total	stat	systematic theo	systematic exp
ggH	$1.12^{+0.37}_{-0.32}$	0.34	0.30	0.13	0.09
VBF	$1.58^{+0.77}_{-0.68}$	0.73	0.69	0.20	0.15
VH	$-0.16^{+1.16}_{-0.79}$	0.97	0.97	0.08	
tt̄H	$2.69^{+2.51}_{-1.81}$	2.2	2.1	0.4	

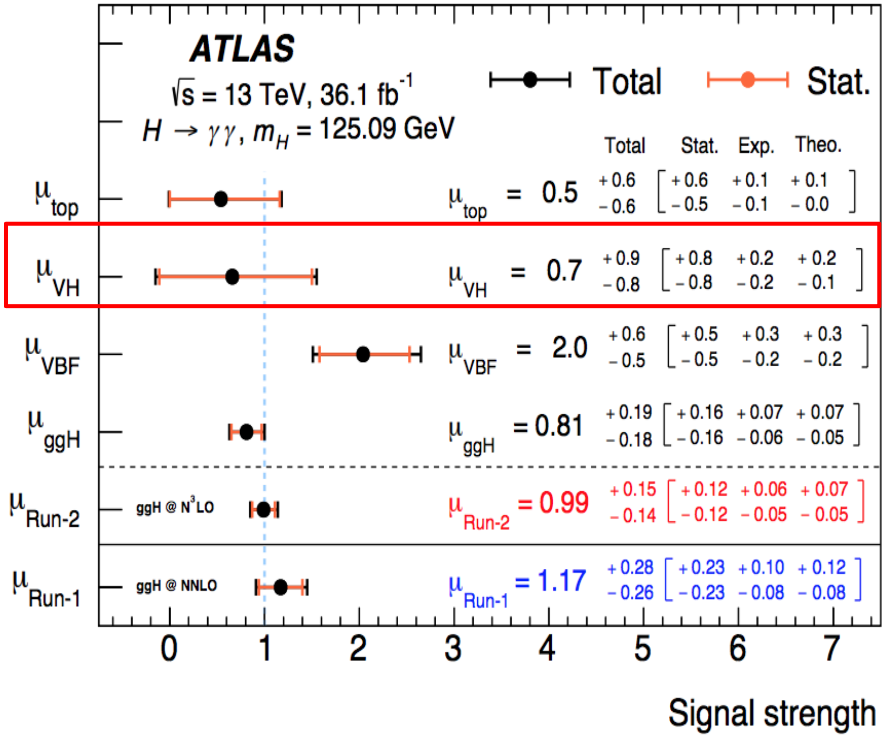
https://arxiv.org/pdf/1802.04146.pdf

H→ γγ: Run 2 ATLAS

Category	Selection
VH dilep	$N_{\text{lep}} \geq 2$, $70\,\text{GeV} \leq m_{\ell\ell} \leq 110\,\text{GeV}$
VH lep High	$N_{\text{lep}} = 1$, $\lvert m_{e\gamma} - 89\,\text{GeV}\rvert > 5\,\text{GeV}$, $p_{\text{T}}^{\ell+E_{\text{T}}^{\text{miss}}} > 150\,\text{GeV}$
VH lep Low	$N_{\text{lep}} = 1$, $\lvert m_{e\gamma} - 89\,\text{GeV}\rvert > 5\,\text{GeV}$, $p_{\text{T}}^{\ell+E_{\text{T}}^{\text{miss}}} < 150\,\text{GeV}$, $E_{\text{T}}^{\text{miss}}$ significance > 1
VH MET High	$150\,\text{GeV} < E_{\text{T}}^{\text{miss}} < 250\,\text{GeV}$, $E_{\text{T}}^{\text{miss}}$ significance > 9 or $E_{\text{T}}^{\text{miss}} > 250\,\text{GeV}$
VH MET Low	$80\,\text{GeV} < E_{\text{T}}^{\text{miss}} < 150\,\text{GeV}$, $E_{\text{T}}^{\text{miss}}$ significance > 8
VH had tight	$60\,\text{GeV} < m_{\text{jj}} < 120\,\text{GeV}$, $\text{BDT}_{\text{VH}} > 0.78$
VH had loose	$60\,\text{GeV} < m_{\text{jj}} < 120\,\text{GeV}$, $0.35 < \text{BDT}_{\text{VH}} < 0.78$





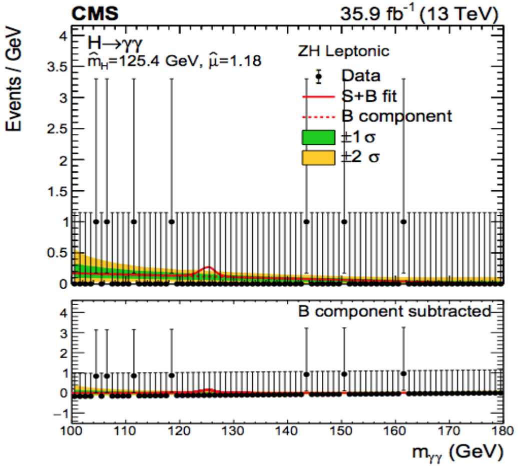


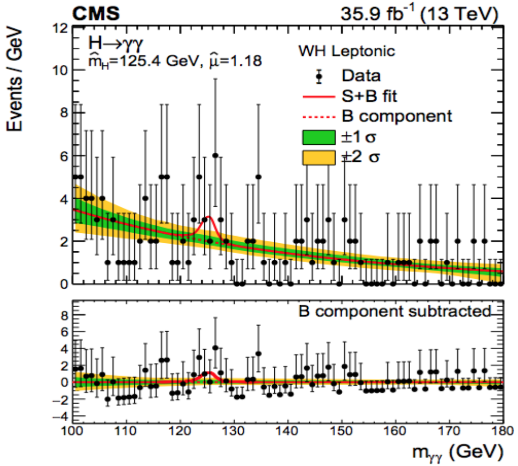
https://arxiv.org/pdf/1804.02716.pdf

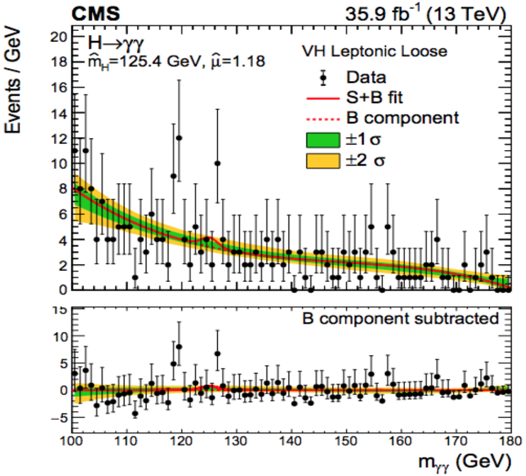
H→ γγ: Run 2 CMS

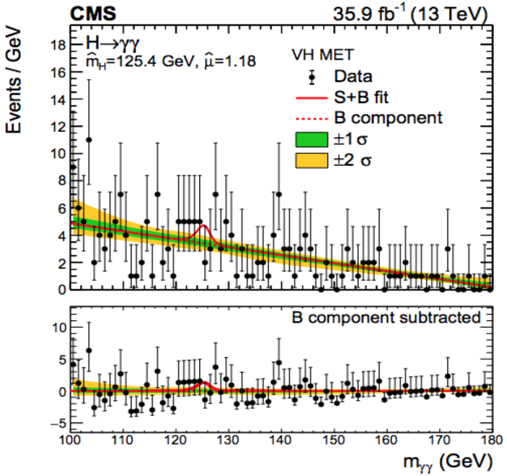
5 categories exploiting the presence of leptons, MET and jets

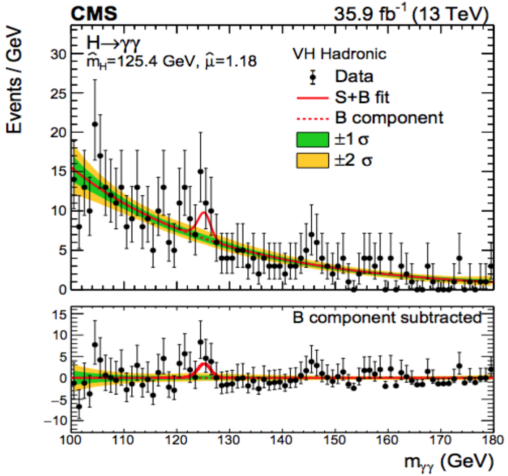
"Each event is classified exclusively by applying the category selections in order and choosing the highest-priority category satisfied by the event."











https://arxiv.org/pdf/1804.02716.pdf

H→ γγ: Run 2 CMS

5 categories → SELECTION

- leptonic Z decays (ZH Leptonic):
  - leading photon $p_T > 3m_{\gamma\gamma}/8$, subleading photon $p_T > m_{\gamma\gamma}/4$;
  - diphoton classifier BDT score greater than 0.11;
  - two same-flavour leptons within the fiducial region, $p_T > 20\,\text{GeV}$; electrons and muons are required to satisfy the same identification criteria as for the ttH Leptonic category;
  - dilepton invariant mass $m_{\ell\ell}$ in the range $70 < m_{\ell\ell} < 110\,\text{GeV}$;
  - $R(\gamma, e) > 1.0$, $R(\gamma, \mu) > 0.5$, for each of the leptons;
  - in addition, a conversion veto is applied to the electrons to reduce the number of electrons originating from photon conversions, by requiring that, when an electron and a photon candidate share a supercluster, the electron track is well separated from the centre of the supercluster: $R(\text{supercluster}, \text{e-track}) > 0.4$.
- leptonic W decays (WH Leptonic):
  - leading photon $p_T > 3m_{\gamma\gamma}/8$, subleading photon $p_T > m_{\gamma\gamma}/4$;
  - diphoton classifier BDT score greater than 0.28;
  - at least one lepton with $p_T > 20\,\text{GeV}$; electrons and muons are required to satisfy the same identification criteria as for the ZH Leptonic category;
  - $R(\gamma, \ell) > 1.0$ and conversion veto as in the ZH Leptonic category;
  - missing transverse momentum $p_T^{\text{miss}} > 45\,\text{GeV}$;
  - up to two jets each satisfying $p_T > 20\,\text{GeV}$, $|\eta| < 2.4$, $R(\text{jet}, \ell) > 0.4$, and $R(\text{jet}, \gamma) > 0.4$;
- W or Z leptonic decays, relaxed selection (VH LeptonicLoose):
  - as for WH Leptonic with the requirement on the missing transverse momentum to be $p_T^{\text{miss}} < 45\,\text{GeV}$;
- W or Z leptonic decays, with at least one missing lepton (VH MET):
  - leading photon $p_T > 3m_{\gamma\gamma}/8$, subleading photon $p_T > m_{\gamma\gamma}/4$;
  - diphoton classifier BDT score greater than 0.79;
  - missing transverse momentum $p_T^{\text{miss}} > 85\,\text{GeV}$;
  - angle in the transverse plane between the direction of the diphoton and the $\vec{p}_T^{\text{miss}}$ $\Delta\phi(\gamma\gamma, \vec{p}_T^{\text{miss}}) > 2.4$;
- hadronic decays of W and Z (VH Hadronic):
  - leading photon $p_T > m_{\gamma\gamma}/2$, subleading photon $p_T > m_{\gamma\gamma}/4$;
  - diphoton classifier BDT score greater than 0.79;
  - at least two jets, each with $p_T > 40\,\text{GeV}$ and $|\eta| < 2.4$, $R(\text{jet}, \gamma) > 0.4$;
  - dijet invariant mass in the range $60 < m_{jj} < 120\,\text{GeV}$;
  - $|\cos\theta^\star| < 0.5$, where $\theta^\star$ is the angle that the diphoton system makes, in the diphoton-dijet centre-of-mass frame, with respect to the direction of motion of the diphoton-dijet system in the lab frame. The distribution of this variable is rather uniform for VH events, while it is strongly peaked at 1 for background and events from ggH production.